THE MICROANALYSIS OF FIXED-INTERVAL RESPONDING

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The fixed-interval schedule of reinforcement is one of the more widely studied schedules in the experimental analysis of behavior and is also a common baseline for behavior pharmacology. Despite many intensive studies, the controlling variables and the pattern of behavior engendered are not well understood. The present study examined the microstructure and superstructure of the behavior engendered by a fixed-interval 5- and a fixed-interval 15-minute schedule of food reinforcement in the pigeon. Analysis of performance typical of fixed-interval responding indicated that the scalloped pattern does not result from smooth acceleration in responding, but, rather, from renewed pausing early in the interval. Individual interresponse-time (IRT) analyses provided no evidence of acceleration. There was a strong indication of alternation in shorter-longer IRTs, but these shorter-longer IRTs did not occur at random, reflecting instead a sequential dependency in successive IRTs. Furthermore, early in the interval there was a high relative frequency of short IRTs. Such a pattern of early pauses and short IRTs does not suggest behavior typical of reinforced responding as exemplified by the pattern found near the end of the interval. Thus, behavior from clearly scalloped performance can be classified into three states: postreinforcement pause, interim behavior, and terminal behavior.

Key words: fixed-interval schedule of reinforcement, pauses, interresponse-time analysis, microanalysis, cumulative record, factor analysis, second-order deviations, pigeons

The fixed-interval schedule of reinforcement is perhaps the simplest schedule of intermittent reinforcement to arrange: The first appropriate response occurring a fixed time after some stimulus event (typically the previous reinforcer) is reinforced. However, the simplicity of the arrangement belies the complexity of the behavior that results.

The behavior engendered by fixed-interval schedules, over a wide range of temporal parameters, has been subjected to intensive study in the experimental analysis of behavior because it models what is called temporal con-

trol. It has also been a focal criterion in behavioral pharmacology because of its sensitivity to chemical challenge. Despite many experiments manipulating the presumed controlling variables, a comprehensive explanation for the pattern of behavior characteristic of fixed-interval responding remains elusive (cf. Zeiler, 1979). The present experiment undertook a microanalysis (Gott & Weiss, 1972; Weiss, 1970; Weiss & Gott, 1972) to clarify the complex relationships among the many possible indices of performance. Such an analysis was based upon the individual interresponse time (IRT—the time elapsing between successive responses meeting the criterion of the response required by the fixed-interval schedule) and the sequence in which IRTs are emitted.

Many textbooks and scientific papers describe the typical pattern of fixed-interval (FI) responding as a pause at the beginning followed by an acceleration in response rate to a high terminal value sometimes described as constant (e.g., Branch & Gollub, 1974; Dews, 1956, 1978; Sanger, 1979). This pause-acceleration sequence is said to be the source for the "scalloped" pattern in the cumulative record. The cumulative records of such performance

provided the base for FI theories, as typified by Skinner (1938) and Ferster and Skinner (1957). Further improvements in the technology of experimental control and data gathering have also advanced our understanding of FI responding. However, many of the data based simply on response counts may be of limited value in theory testing because individual IRTs are buried by averaging across intervals (Branch & Gollub, 1974). Results derived from averaging are further confused by sequential dependencies between successive intervals in both numbers of responses and of pauses (Dews, 1970; Ferster & Skinner, 1957; Gentry & Marr, 1982; Lowe & Wearden, 1981; Shull, 1971; Skinner, 1938; Wearden, 1979).

A slightly different pattern of responding, called "break-and-run," has also been noted in some experiments. As the name indicates, it describes an abrupt transition from no responding (the pause after reinforcement) to a high constant rate of responding. This pattern is what might be expected if the FI schedule generated behavior similar to that which would be generated by a compound schedule of extinction followed by a variable interval (VI) schedule of reinforcement (Schneider, 1969). The extinction schedule maintains a low or zero response rate; it is then followed by the VI schedule that maintains a constant high response rate. This theory has not been widely accepted because the scalloped pattern is far more common than break-and-run.

Since acceleration in response rate is such an important theoretical aspect of FI responding, several experiments have sought to document the pervasiveness of acceleration in individual intervals. Branch and Gollub (1974) found acceleration in responding by pigeons when they defined it as rate increases in successive tenths of the interval for FI 300-sec, FI 100-sec, and FI 40-sec. Dews (1978) performed an analysis of FI 1000-sec responding in two monkeys (*M. mulatta*) based on ten 100-sec bins. The averaged rates generated in individual intervals were consistent with an acceleration process. However, as Dews (1978) noted, "Continued progress in understanding FI responding will probably require studies on average rates of responding over short periods, as well as analysis at the level of individual IRTs" (p. 73). Staddon and Frank (1975) analyzed responding under short FIs (33 sec and 120 sec) with short bin widths. Their results corresponded to

those of Dews (1978). In these three studies response rate was averaged over the bin width (3 and 12 sec with Staddon and Frank; 100 sec with Dews; 30, 10, and 4 sec with Branch and Gollub) and may not accurately reflect events at the level of individual IRTs.

Dews (1978) further found that the rate of responding depended upon its temporal proximity to the onset of responding (or number of prior responses, since the two are confounded) but not on the time since the beginning of the interval. This result partially agrees with the results from a study by Shull and Brownstein (1970), who found that the median IRT for the first six responses was a function of the time since the beginning of the interval. After the first six, the median IRT remained approximately constant. Dews (1978) speculated that the decrease in IRTs throughout the interval (i.e., the acceleration in rate) might have been too small to detect in their analysis, even though present. Since FI responding generally produces a multimodal IRT distribution in the pigeon (e.g., Schaub, 1967), one must also question the adequacy of the median as a representative measure.

Since the FI schedule requires that some minimum time elapse before a reinforcer becomes available, longer IRTs are more likely to be reinforced than shorter ones, because the interval is more likely to end during the longer period (Morse, 1966). It is still not clear how the distribution of the reinforced IRTs is related to the distribution of IRTs throughout the interval or during the terminal response portion (Dews, 1969).

A microanalysis has the potential of answering some of these questions. (1) If there is acceleration on the level of individual IRTs, then a significant proportion of them should be shorter than the preceding IRTs. (2) If IRT duration is a function of the number of preceding responses, then plots of IRT distribution as a function of ordinal position should show such a trend. The same argument holds for control of the IRT distribution by time since the interval began. (3) Comparison of the reinforced IRT distribution with the other IRT distributions should clarify how the reinforced IRT helps determine the pattern of responding. (4) Finally, there may be a sequential dependency in the IRTs not visible in cumulative records or IRT distributions. That is, each IRT might be controlled partially by the im-

mediately preceding IRT as well as by other factors.

On a more molar level, analyses can examine the relationships among many indices of performance. The current analysis differs from previous efforts in using exact measures of quarter life (percentage of interval elapsed when one fourth of the responses have been emitted; Herrnstein & Morse, 1957) and of index of curvature (a measure of deviation from constant response rate; Fry, Kelleher, & Cook, 1960), in specifying pauses and in providing the same measures across intervals (i.e., including dynamic effects as described by Gentry & Marr, 1982; Shull, 1971; Skinner, 1938). Only a few correlations of the many possible combinations of variables have ever been reported (e.g., Dukich & Lee, 1973; Gollub, 1964).

METHOD

Subjects

The subjects were two male White Carneaux pigeons (P2 and P4) maintained at approximately 80% of their free-feeding weights. Approximately one year earlier each subject had experimental experience under a variable-interval schedule of reinforcement with an IRT requirement imposed. That experiment was conducted in a different chamber (Coulbourn modular chamber) with different stimuli.

Apparatus

A Foringer operant-conditioning chamber (No. 1102) was used in this experiment. The chamber contained two response keys; however, only the left key was operative, requiring a minimum force of .15 N to operate and, when operated, providing auditory feedback via a telegraph sounder. A feeder that allowed 6-sec access to mixed grain was located midway between the two keys and below them. The chamber was illuminated by two 6-W lights behind the wall opposite the response keys. The response key was transilluminated by a white light from a 28-V dc lamp. Masking noise was present throughout experimental sessions. The programming and recording of events was controlled by a PDP 8/e minicomputer operating under the SUPERSKED system (Snapper & Inglis, 1979). All interevent times in 10-msec resolution were recorded in real time for later analysis.

Procedure

Since both pigeons had been trained previously with food delivery contingent upon key pecking, they were placed directly under the schedules for the present experiment without any additional training. P2 was maintained on a FI 15-min and P4 on a FI 5-min schedule of reinforcement. The pigeons usually were tested five days per week. Each session lasted for 20 intervals. The data for the present experiment are derived from Sessions 23 to 44 when there was no apparent trend in overall responding or pattern.

RESULTS AND DISCUSSION

Conventional Data Analysis

Since the credibility of the microanalysis depends upon whether the performance that was analyzed is typical of fixed-interval behavior, several conventional indices are included. Figure 1 shows cumulative record segments from a session that reflects the stable performance of each pigeon. The pattern in the records is a pause followed by some curvature leading toward a high steady rate near the end of the interval. Some other features in the records are also typical of FI responding (Ferster & Skinner, 1957). For example, there is occasional rough grain (obvious renewed pausing after responding had begun) and knees (decelerating responding early in an interval). Nothing in these records seems to indicate atypical FI responding.

Table 1 summarizes the number of responses per interval, index of curvature (an exact measure based on IRTs recorded by the computer), and postreinforcement pause durations for the two pigeons. These data are the means for a session of 20 intervals averaged over 21 sessions. The standard deviations are the mean of the session standard deviations for the 21 sessions. The standard errors are the standard deviations of the 21 session means. The discrepancy from the expected $1:\sqrt{20}$ relationship between the standard deviation and the standard error reflects the fact that some of the within-session variability is accounted for by the sequential structure across successive intervals (we thank P. B. Dews for pointing out this relationship). Nothing in these measures suggests atypical performance.
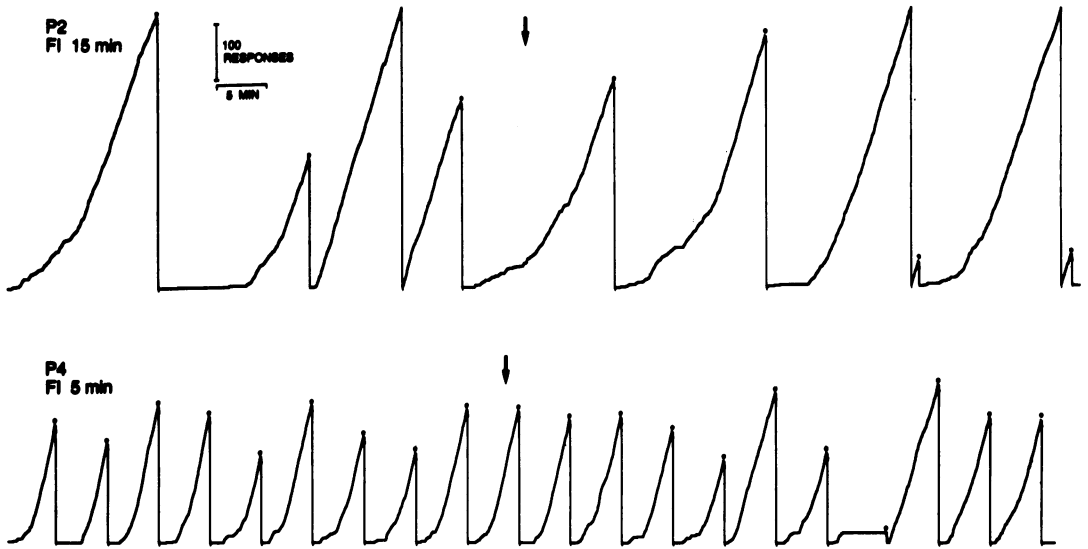
Fig. 1. Typical cumulative records. The top record for P2 under FI 15 shows seven complete intervals; the lower record for P4 under FI 5 shows a complete session. The dots indicate the reinforcement delivery. The arrows indicate the intervals selected for further analysis (see Figure 3).

Although averaging performance to obtain the "average scallop" has been found to be a faulty analytical technique (Branch & Gollub, 1974; Dews, 1978), such a procedure does produce an easily recognized form. Figure 2 shows the mean cumulative responses for each pigeon as a function of the percentage of the interval elapsed. On the average, responding accelerated throughout the interval.

All of these conventional measures indicate that the procedure maintained typical FI behavior. Thus, the results of further analysis

should be an accurate description of FI microstructure.

Cumulative Record Analysis

To the experienced worker in operant conditioning, cumulative records reveal useful, detailed relationships in responding over time. Therefore, a technique was developed to take the sequential IRT data recorded during a ses-

Table 1

Conventional Measures of Performance for Fixed-interval Behavior.

	P2 FI 15	P4 FI 5
Responses per interval	409.8	167.2
(S.D. per session)*	257.3	69.0
(S.E. from session means)**	84.1	54.7
Index of curvature	0.444	0.382
(S.D. per session)	0.281	0.140
(S.E. from session means)	0.080	0.042
Pause in seconds	173.1	51.9
(S.D. per session)	228.9	38.6
(S.E. from session means)	76.6	15.7

*Represents the standard deviation from single sessions of 20 intervals averaged over 21 sessions.

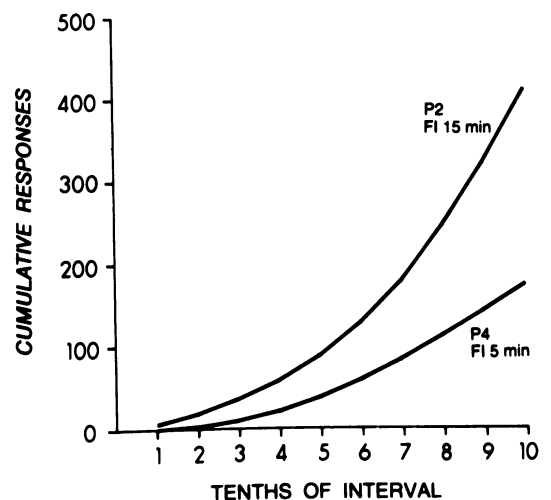**Represents the standard deviations of the session means.

Fig. 2. Average scallop. These curves show the average total number of responses made at each tenth of the interval. The average was based on 21 sessions of 20 intervals.

sion and, with or without intervening manipulations, create a synthetic cumulative record. In the following analysis one interval for each pigeon was selected and the sequences of individual IRTs were processed so that successively shorter IRTs were eliminated from the cumulative record.

The intervals that were selected are marked in Figure 1 by the arrows. These intervals were selected because they appeared scalloped, showing an initial pause and a high steady terminal rate. They were typical of what would be identified as FI responding. The two leftmost records in Figure 3 are the synthetic reproductions of the originals before any manipulations based upon the IRTs. These reproductions are faithful replicas of the originals. Given with each interval are number of responses and index of curvature.

The remaining curves in Figure 3 were produced by successively eliminating greater and greater ranges of IRTs from the data, starting with a very long IRT. These maximum retained IRTs were, respectively, 20, 10, 5, 3, 2, and 1 sec; any IRT longer than this maximum was deleted, contributing neither horizontal nor vertical excursion to the record. The number of retained responses and the resulting index of curvature are shown with each record.

Two features of FI performance become clear using this technique. First, a few long IRTs make the dominant contribution to the index of curvature. Second, when only the shorter IRTs are retained, the index of curvature falls toward zero and then becomes negative. This would indicate that both the longest IRTs and the shortest IRTs occur early in the interval. Since the longer IRTs contribute far more to the index of curvature than the shorter ones, the original index of curvature is positive even though the short IRTs are far more numerous.

Although these two records were selected on the basis of their resemblance to prototypical FI performance, it is conceivable that other intervals would not show such a relation. There-
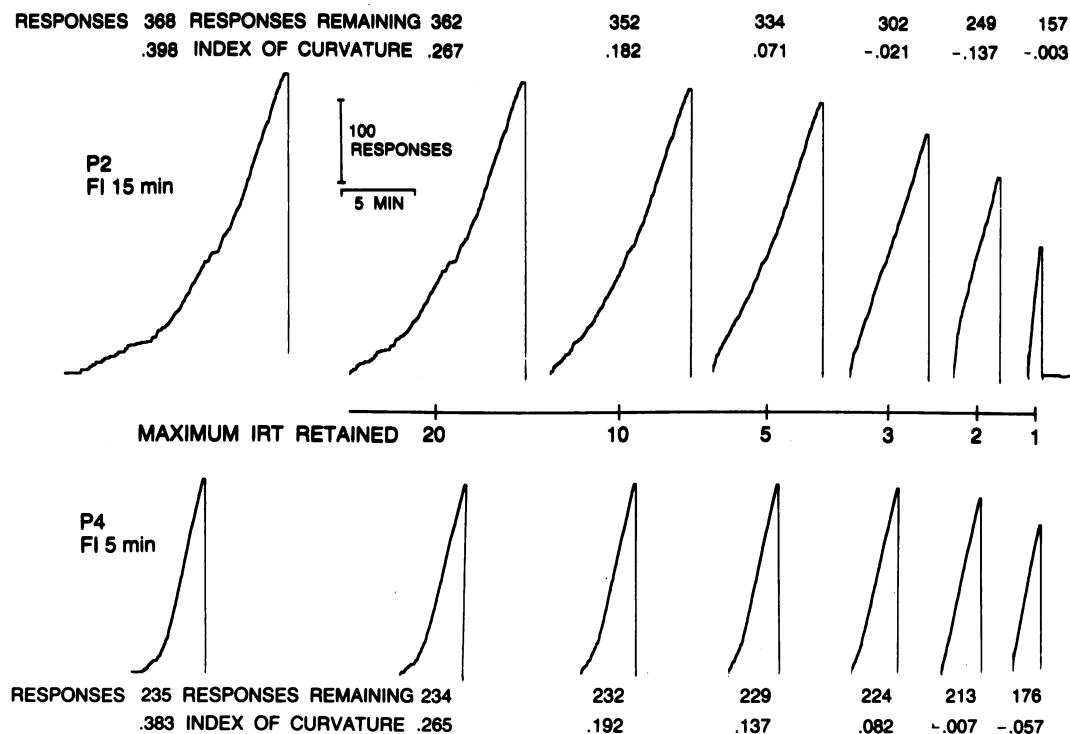

Fig. 3. Synthetic cumulative records. The two records on the left (upper and lower) are the synthetic reproductions of the two intervals marked with arrows in Figure 1. Above the upper and below the lower records are the numbers of responses and the indices of curvature. To the right of each record is a series of reproductions of that record with successively shorter maximum IRTs, starting with 20 sec and decreasing to 1 sec. Any IRT longer than the maximum IRT was deleted from the record. Given with each of these records are the remaining number of responses and the resulting index of curvature.

fore, the index of curvature was calculated for every interval of the 21 sessions (420 intervals in all) as a function of the maximum retained IRT. Figure 4 shows the resulting index of curvature as a function of the IRT limit with the normal (unaltered) index of curvature shown on the right. The trend shown by the selected intervals reflects accurately the trend shown by all intervals. For P2, the index of curvature dropped from .44 to .11 when IRTs greater than 20 sec were eliminated. The comparable drop for P4 was .38 to .19. As the maximum IRT progressively decreased, the index of curvature fell. Still further decreases in the IRT limit produced negative curvature, not only on the average across the 420 intervals but with more than 80% of the individual intervals. Data for all intervals, then, verify results from the synthetic records for a single interval: A very few long IRTs account for a large proportion of the index of curvature, and the highest concentration of short IRTs occurs early in the interval.

Within-interval Variability

The tendency for both very long and very short IRTs to occur early in the interval was shown in the preceding section. More detailed analysis is possible by looking for changes in the IRT distribution within intervals. Since each IRT was recorded in real time, it was possible to plot their distributions by ordinal position and by time since the interval began.

Figure 5 is an isometric projection of the IRT distribution in 50-msec bins for the first 320 responses of an interval. The responses have been grouped in fours (excluding the postreinforcement pause in the first group of four) to increase sample size. Each ordinal-response position is based on four IRTs times 420 intervals except for intervals that did not contain that many responses (i.e., the sample size decreased at the higher range, especially for P4 under FI 5-min). The height of each peak is the relative frequency of that IRT for that ordinal-response position. The last bin (far left, which is the relative frequency for IRTs of 5.0 sec or greater) was reduced in height by one-half relative to the other bins to maintain perspective of the surface.

Several features of FI responding are revealed in this figure. First, there is a ridge of very short IRTs whose relative frequency changes little through the interval. Second, as
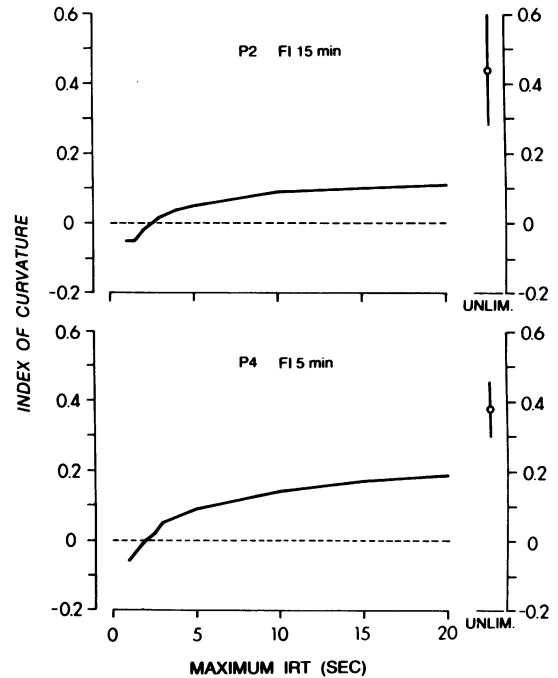

Fig. 4. Mean indices of curvature. The point on the right is the mean index of curvature for all intervals in the 21 sessions plus and minus one standard error. The function shows the mean index of curvature for the same intervals when the maximum retained IRT is restricted from 20 sec down to 1 sec (from right to left). The dashed line shows an index of curvature of 0.0, which would reflect a constant response rate throughout the interval.

responding proceeds, moderate IRTs rise in frequency. Third, there is a rapid drop in the relative frequency of very long IRTs as responding proceeds. One striking aspect of this figure is the lack of obvious acceleration that would be indicated by a mound of IRTs moving toward the shorter values. Instead, as the relative frequency of long IRTs decreases, the relative frequency of the shorter IRT modes increases. Plots based upon time from the beginning of the interval show similar relations. However, a three-dimensional plot based on responses (Figure 5) is confounded with time since beginning of interval; likewise, a plot based upon time into interval is confounded with number of preceding responses. Figure 6 shows an attempt to separate the two factors by dividing the interval into tenths. Each row contrasts IRT distributions based on responses (early in responding and late in responding). Each column contrasts IRT distributions based on time into interval (fourth and tenth
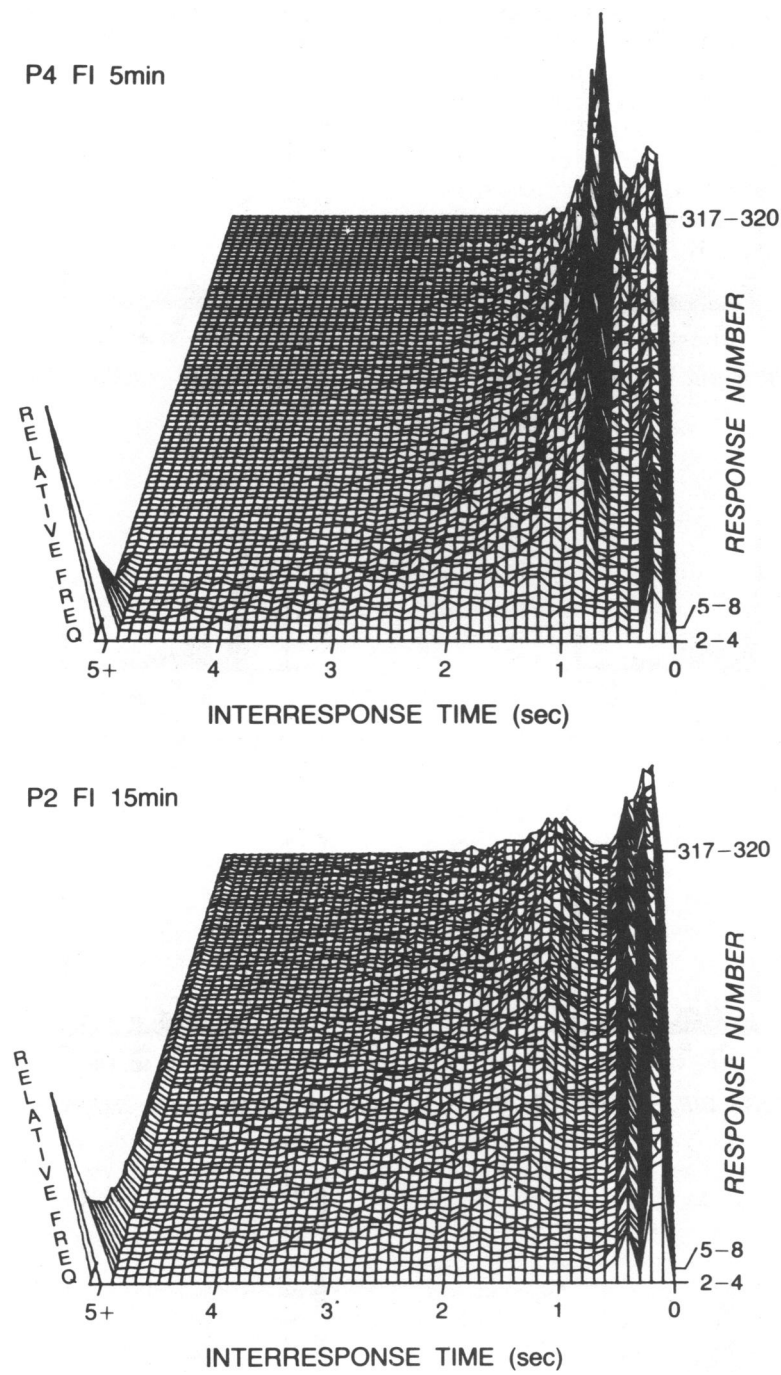
Fig. 5. IRT distribution by ordinal position. These three-dimensional plots show IRT distributions in 50-msec bins as a function of the ordinal position of the responses in the interval. The responses have been grouped by fours to increase sample size. The relative frequency in the last bin (5+ sec) has been decreased by one half in order to maintain perspective for the remainder of the figure. As number of responses increases, the sample size decreases since all intervals did not have equivalent numbers of responses.

P2 FOURTH BIN – RESPS. 2–25
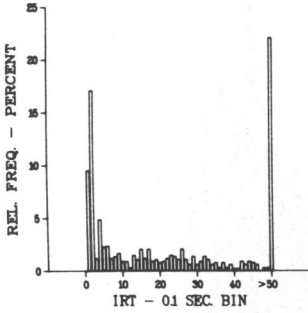
P2 TENTH BIN – RESPS. 2–25
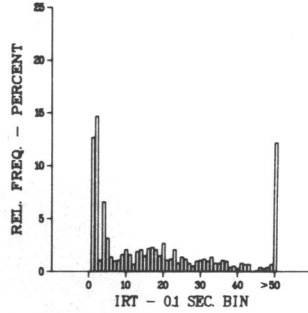
P2 FOURTH BIN – RESPS. 100–120
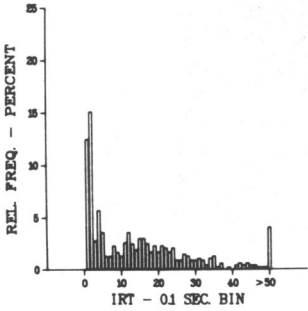
P2 TENTH BIN – RESPS. 100–120
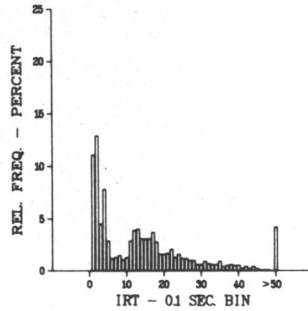
P4 FOURTH BIN – RESPS. 2–25
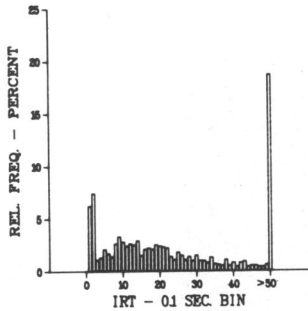
P4 TENTH BIN – RESPS. 2–25
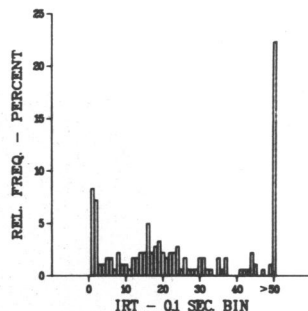
P4 FOURTH BIN – RESPS. 50–70
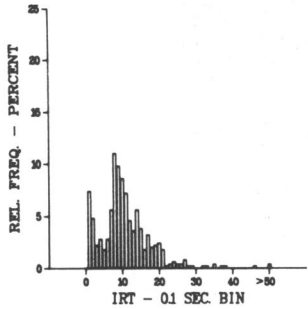
P4 TENTH BIN – RESPS. 50–70
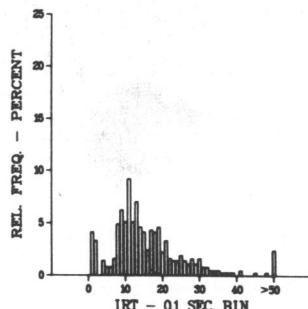
Fig. 6. IRT distribution by time and ordinal position. The upper panels for each pigeon show the IRT distribution for Responses 2 to 25 early in the interval (fourth tenth) and late in the interval (tenth tenth). The lower panels for each pigeon show the distributions later in responding (50 to 70 for P4 and 100 to 120 for P2) but during the same interval segments.

segments). Classification by ordinal-response position is far more uniform than classification by segment.

Since long IRTs appear to play an important role in the pattern of responding, they were subjected to further analysis. There have been previous discussions on the nature of the long IRTs that tend to occur at the beginning of the interval (e.g., Killeen, 1975; Premack, 1965; Schaub, 1967; Shull & Brownstein, 1970; Zeiler, 1979). If it is assumed that, during long IRTs, the pigeon is engaging in activity not involved in key pecking, then it is reasonable to label such IRTs as "pauses" in responding, or as intervals between bouts of responding. Dews (1956) included an analysis of pausing in a study of drug effects on FI responding. Such an analysis requires a method of deciding when the time between key pecks is an IRT and when it is to be considered a pause. A basis for such a decision is a plot of percentage of responses terminating a "pause" for various temporal criteria of a pause, as shown in Figure 7. One striking feature of this figure is that both pigeons follow nearly the same function, even though one is on FI 5 and the other FI 15.

If an arbitrary value of 5% is taken as the estimate of responses that terminate "true" pauses, then the pause-time criterion is approximately 3.5 sec, a value also close to the point of inflection. It is reasonable to assume that when more than 3.5 sec have elapsed between responses, the pigeon is probably engaged in some activity other than key pecking. If this criterion is applied to Figure 4, then the index of curvature for each pigeon averages less than .05; i.e., the removal of what might be called legitimate pauses in responding eliminates all but the slightest curvature.

Based on a pause criterion of 3.5 sec, the original data were analyzed to calculate the mean duration of each successive pause in the interval, regardless of ordinal position relative to other responses or to time since initiation of responding. Figure 8 shows a steep decrease in the mean pause duration as a function of the number of preceding pauses. Pausing, then, "decelerates" through the interval. The arguments of Branch and Gollub (1974) on the danger of averaging responding with post-reinforcement pausing across intervals should apply also to renewed pausing within an interval.

Strictly speaking, the early pauses in responding are not simply interposed in normal responding nor do they separate trains of responding. As shown earlier, the short IRTs early in the interval are very short and the incidence of IRTs in the .5 sec or greater range is less than its incidence later in the interval.

Fig. 7. Pausing as a function of the pause criterion. Both pigeons followed nearly the same function for percentage of responses terminating pauses for the various pause criteria.

Fig. 8. Pause duration as function of ordinal position of pause. For a pause criterion of 3.5 sec, the mean pause was calculated as a function of the number of preceding pauses, regardless of where in the interval the pauses occurred. Since all intervals did not have 16 pauses (IRTs exceeding 3.5 sec), the sample size decreased for later ordinal values. The first pause is the postreinforcement pause.

Thus, long pauses early in the interval tend to separate high-rate bursts.

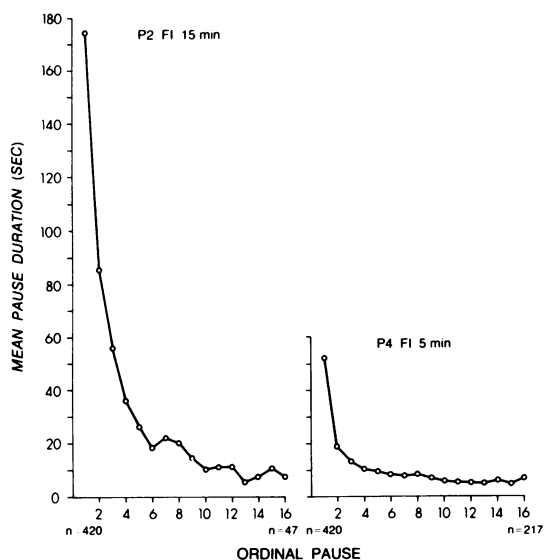Three lines of evidence indicate that the long IRTs are the source of the curvature in the cumulative record: (1) As responding proceeds, long IRTs decrease in relative frequency; (2) if excised from the response stream, the typical FI curvature is eliminated; (3) mean pause duration decreases through the interval. A comprehensive analysis of the sources of curvature, however, should include the sequential properties of IRTs since averaging over 420 intervals might mask some subtle acceleration in responding. If acceleration in response rate exists, it should be evident in the sequence of individual IRTs.

Sequential Relations in IRTs

Each IRT was recorded in the order in which it was emitted, making it possible to analyze sequential effects. If response rate is characterized as "smoothly accelerating," each IRT should be shorter than its immediate predecessor. Of course, such extreme regularity is not normally found in behavior; however, a convincing percentage of the IRTs should be shorter than the preceding IRTs if the term "acceleration" is to be used legitimately. Although concavity in the cumulative records clearly exists for FI responding, it does not necessarily follow that local response rates smoothly increase.

The first analysis was simply a count of how many IRTs were shorter than, equal to (with 10 msec resolution), or longer than the preceding IRT. (The postreinforcement pause was excluded from the count.) For P2, the relative frequency of an IRT shorter than the preceding IRT was .486; for P4, the relative frequency of a shorter IRT was .499. Thus, there is no evidence for acceleration in response rate when all averaging is eliminated from the analysis. Averaging, even for bins within individual intervals as used by Dews (1978) and Branch and Gollub (1974), probably provided the basis for assuming acceleration. The detail extracted in this microanalysis is far finer than can be seen in cumulative records. Visual averaging of the fine grain produced by short pauses and the relatively thick lines of the cumulative record may also account for the apparent acceleration.

The nearly equal proportions of short-long and long-short sequences is itself an enticing finding. It could reflect alternation of longer-shorter pairs of responses. A single session for each pigeon was analyzed for runs of successively shorter IRTs. A run of Length 1 was defined as a single IRT shorter than the preceding IRT when both the preceding and succeeding IRTs were longer than their preceding IRTs. A run of Length 2 was two IRTs in a row shorter than their preceding IRTs and preceded and succeeded by IRTs that were longer than their preceding IRTs. This procedure was extended through run Length 7 (seven successively shorter IRTs between two IRTs that were longer than their immediate predecessor). The percentage of IRTs shorter than their preceding IRTs for this session was .487 for P2 and .501 for P4, two values that are very close to those for all 21 sessions. Since this percentage is an estimate for the probability of an IRT being shorter than the preceding IRT, then the probability for each run length can be calculated by assuming that the sequence of shorter or longer IRTs is random according to the binomial process. For example, let p represent the probability of a shorter IRT and q $(1 - p)$ represent the probability of a longer (or equal) IRT. Then the probability of a run of Length 1 is $q \times p \times q$; the probability of a run of Length 2 is $q \times p \times p \times q$; for run Length 3, $q \times p \times p \times p \times q$; etc. If the sequence of shorter and longer IRTs is a random selection from this binomial process, then the obtained relative frequency for each run length will match this theoretical probability. These data are shown in Figure 9. There were far more runs of Length 1 than would be expected by chance; the same was true for runs of Length 2. For runs of Length 3 through 7, there were fewer than would be expected by chance. Thus, there was indeed far more alternation in shorter-longer patterns than would be expected by chance.

Since the greatest deviation from chance occurred for run Length 1, a finer analysis of the alternation pattern was performed to detect further sequential structure in the response pattern. Figure 10 (top panels) is an isometric projection of the relative frequency of pairs of IRTs, i.e., the relative frequency of IRT $n + 1$ given the value of IRT n, in 50-msec bins between 0 and 3 sec with the last bin containing all IRTs greater than 3.0 sec.

The individual peaks in the top panels show which pairs of IRTs occurred more fre-
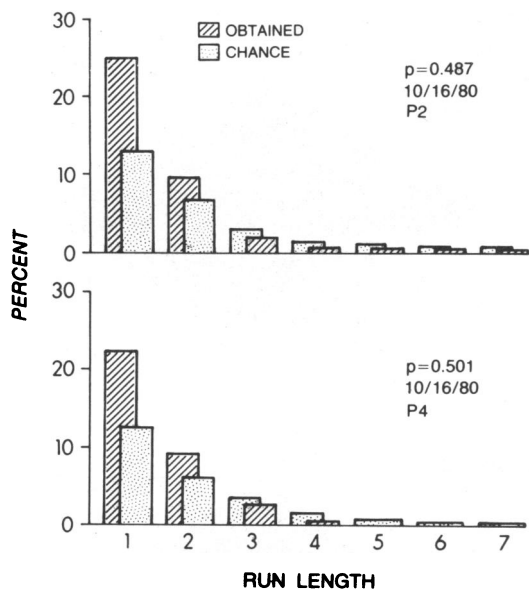
Fig. 9. Percentage of responses becoming successively shorter. A run length of size *n* was defined as *n* IRTs in a row being shorter than their preceding IRTs and these *n* IRTs having an IRT longer than the preceding IRT before and after them. Thus, a run length of *n* has *n*, and only *n*, successively shorter IRTs. The striped bars show the obtained percent of each run length; the stippled bars show the percentage that would be expected by a random selection of shorter-longer IRTs according to a binomial process with *p* being the probability of a "shorter" and *q* being the probability of a "longer" ($q = 1 - p$). Shorter and longer were determined with 10-msec resolution ("equals" were not frequent and were included with the longer count).

quently in that sequence. For example, if the *n*th IRT was greater than 3.0 sec (last bin), then IRT *n* + 1 was very short or very long. If IRT *n* was very short, then IRT *n* + 1 was very short, moderate, or very long. Moreover, this distribution is not randomly spread over the surface of Figure 10; instead, there seems to be a consistent sequential pattern peculiar to each pigeon.

To test this hypothesis of nonrandom selection, the middle panels of Figure 10 were generated from the assumption of a random selection of IRT *n* + 1 for any value of IRT *n*, i.e., no sequential dependency. To generate these surfaces, the probability of a particular IRT following another particular IRT was calculated as the product of the probability (relative frequency) of each of the two IRTs, the assumption of independence of two events. These predicted surfaces were then subtracted from the obtained surfaces to yield the differ-

ence, the surfaces shown in the lower panels of Figure 10. A peak above the plane indicates a pair of IRTs occurring in sequence more often than expected by chance; a peak below the plane of the axes indicates a pair of IRTs occurring less often than would be expected by chance.

The lower panels of Figure 10 clearly indicate that the sequence of IRTs is not generated (or emitted) randomly from the total IRT distribution. Certain combinations are more likely and others less likely to occur than would be expected by chance. In particular, a long IRT is more likely to follow a long IRT than predicted; however, a short IRT is not more likely to follow a short IRT. A moderate IRT is not likely to precede or follow a long IRT, which is further evidence that early in the interval the IRTs are very short or very long with few moderate IRTs.

Higher Level Structure in Responding

Gollub (1964) and Dukich and Lee (1973) reported the relationships among several indices of FI responding. The data from this experiment have been analyzed similarly, but with the inclusion of more variables and exact measures for some of these (index of curvature and quarter life). The variables included amount of time spent in renewed pausing (IRTs greater than 3.5 sec), amount of time spent in moderate and short IRTs (between .5 and 3.5 sec and less than .5 sec, respectively), the postreinforcement pause, quarter life, index of curvature, total responses, and running rate. The intercorrelation matrix for these eight variables for each pigeon is shown in Table 2. The values in this table are the average correlations for the 21 sessions.

There is clearly a complex relationship among these measures. To simplify these relationships, a factor analysis was performed to determine if a simple structure could account for the observed correlations. A principal-components analysis (BMDP4M, Dixon & Brown, 1979) found for each pigeon two factors with eigenvalues greater than 1.0. These two factors accounted for 78% of the total variance for P4 and 83% of the variance for P2. Following this analysis, a varimax orthogonal rotation of the two factors was performed. The resulting factor loadings are shown in Table 3. The distribution of these eight variables in the two
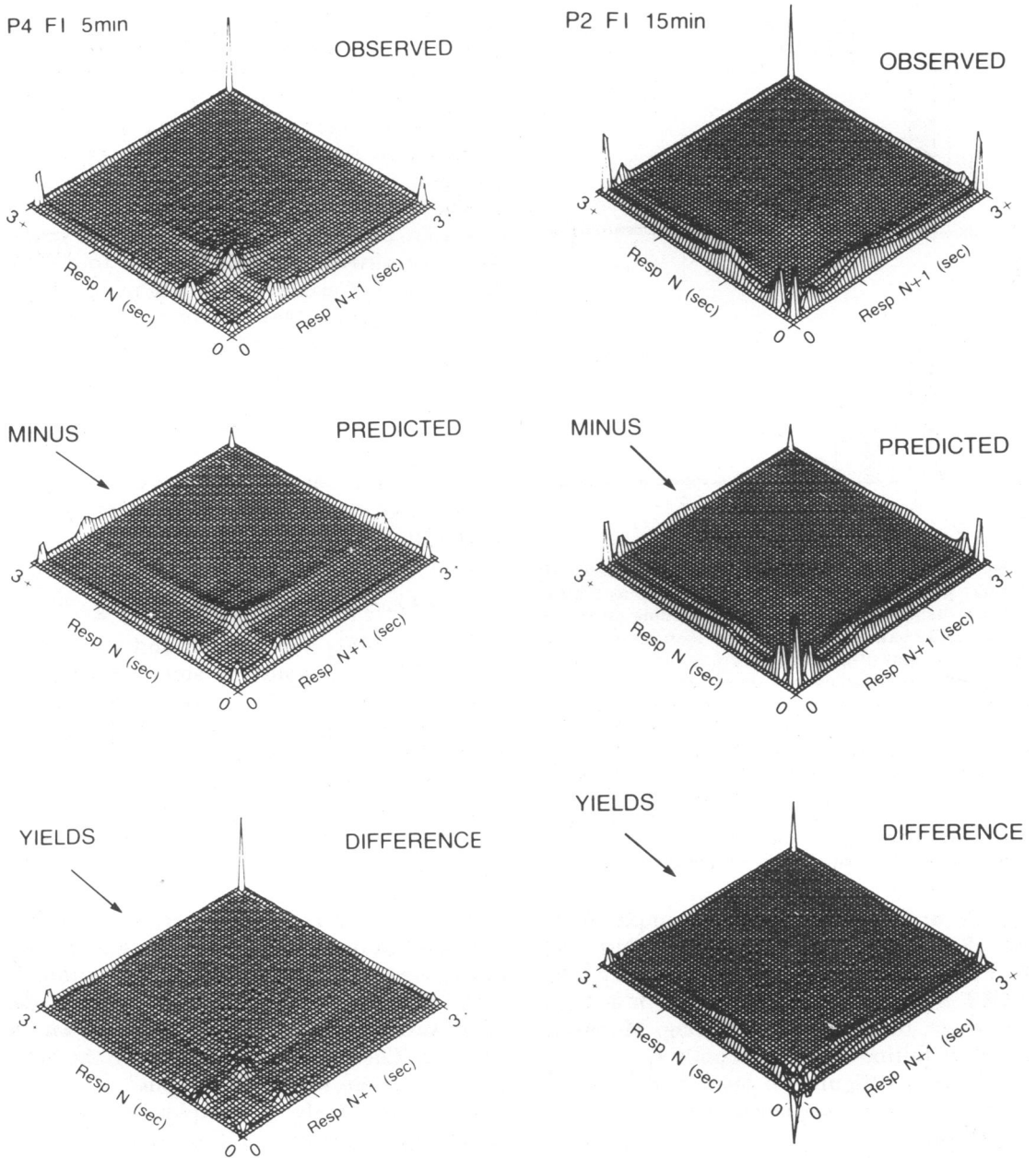
Fig. 10. Isometric projection of sequential effects in pairs of IRTs. *Top panels:* For each pigeon this surface is a three-dimensional IRT distribution in 50-msec bins. The IRT distribution for IRT $n + 1$ is presented as a function of IRT n. For any value of IRT n, a slice perpendicular to that axis will give the IRT distribution for the next response. Of course the plot may be read in the other direction also: For any value of IRT $n + 1$, the distribution of the preceding IRT (IRT n) may be read. The height of each peak indicates the relative frequency of that pair of responses occurring in that particular order, based on the 21 sessions of twenty intervals. *Middle panels:* To determine if the structure in the top panel is random, a random structure was needed for comparison. If the total IRT distribution were sampled at random, then the probability of any pair of IRTs is the product of the probabilities of each IRT alone, i.e., the assumption of independence of two events. The middle panel shows these probabilities for all pairs of IRTs. *Lower panels:* Subtracting the middle panel from the top panel yields the lower panel. Since the top panel was obtained and the middle panel was the chance prediction, the lower panel reflects where behavior deviated from chance levels. A peak above the plane indicates a pair of IRTs occurring more often than expected by chance and a peak below the plane indicates a pair of IRTs occurring less often than expected by chance.

Table 2

Intercorrelation Matrix for Eight Measures of FI Performance.

		A	B	C	D	E	F	G	H
	A. Renewed Pausing	1.00							
	B. Moderate IRTs	−0.52	1.00						
	C. Short IRTs	−0.48	0.88	1.00					
	D. Postreinf. Pause	−0.56	−0.37	−0.32	1.00				
P 2	E. Quarter Life	0.09	−0.47	−0.38	0.33	1.00			
	F. Index of Curvature	−0.03	−0.47	−0.41	0.45	0.84	1.00		
	G. Responses	−0.50	0.97	0.93	−0.35	−0.44	−0.48	1.00	
	H. Running Rate	−0.85	0.74	0.73	0.20	−0.15	−0.18	0.73	1.00

		A	B	C	D	E	F	G	H
	A. Renewed Pausing	1.00							
	B. Moderate IRTs	−0.74	1.00						
	C. Short IRTs	−0.44	0.49	1.00					
	D. Postreinf. Pause	−0.19	−0.47	−0.25	1.00				
P 4	E. Quarter Life	0.40	−0.55	−0.18	0.34	1.00			
	F. Index of Curvature	0.31	−0.69	−0.29	0.57	0.77	1.00		
	G. Responses	−0.68	0.86	0.76	−0.39	−0.40	−0.55	1.00	
	H. Running Rate	−0.78	0.78	0.76	−0.13	−0.28	−0.43	0.90	1.00

dimensions defined by the orthogonal factors is shown in Figure 11.

The results of this analysis indicate that two factors account for most of the FI variance. The variables renewed pausing, short and moderate IRTs, responses, and running rate load heavily on the first factor, accounting for over 55% of the total variance for each pigeon. The second factor primarily contains the variables index of curvature, quarter life, and post-reinforcement pause. Given such loadings, these factors might be labeled "output" and "FI pattern." Furthermore, these two factors seem to be relatively independent of each

Table 3

Factor loadings for eight measures of FI responding on the two factors from a principal-components analysis with varimax rotation of the two factors. The variables are arranged by loadings with loadings of less than .25 replaced by zero. See text for definitions of these variables.

| | Pigeon 2 | | Pigeon 4 | |
| | Factor | | Factor | |
Variable	1	2	1	2
Running Rate	0.96	0.00	0.96	0.00
Renewed Pausing	−0.89	−0.36	−0.88	0.00
Responses	0.82	−0.50	0.87	−0.39
Moderate IRTs	0.82	−0.50	0.74	−0.57
Short IRTs	0.81	−0.44	0.76	0.00
Postreinforcement Pause	0.00	0.85	0.00	0.83
Index of Curvature	0.00	0.83	−0.30	0.87
Quarter Life	0.00	0.75	0.00	0.75

other. Only some of the Factor 1 variables have any appreciable loading on Factor 2, with a tendency for higher "output" to be associated with less "FI pattern." The consistency between the two pigeons, under two different FI values, supports this analysis. Consistent with the preceding analysis, the renewed pausing is different from the other classes of IRTs.

Interval-to-interval dynamics, called second-order deviations by Skinner (1938), were also examined for higher level structure. Previously, Shull (1971) had shown a negative correlation between successive postreinforcement pauses. Gentry and Marr (1982) found similar relationships for responses in successive intervals (cf. Dews, 1970; Lowe & Wearden, 1981; Wearden, 1979). The data from the present experiment make many more comparisons possible. Table 4 gives the lag-1 correlations for the following variables: responses, postreinforcement pause, index of curvature, running rate, and renewed pauses. These values are the mean lag-1 correlations for the 21 sessions. As reported in previous studies, these values are small; however, there is marked consistency in the sign of the relationships. If there were no correlation between measures in successive intervals, then we would expect about half of the 21 sessions to show a positive lag-1 correlation and half a negative correlation; i.e., there would be a 50-50 chance of the correlation being positive or negative. The tendency for the
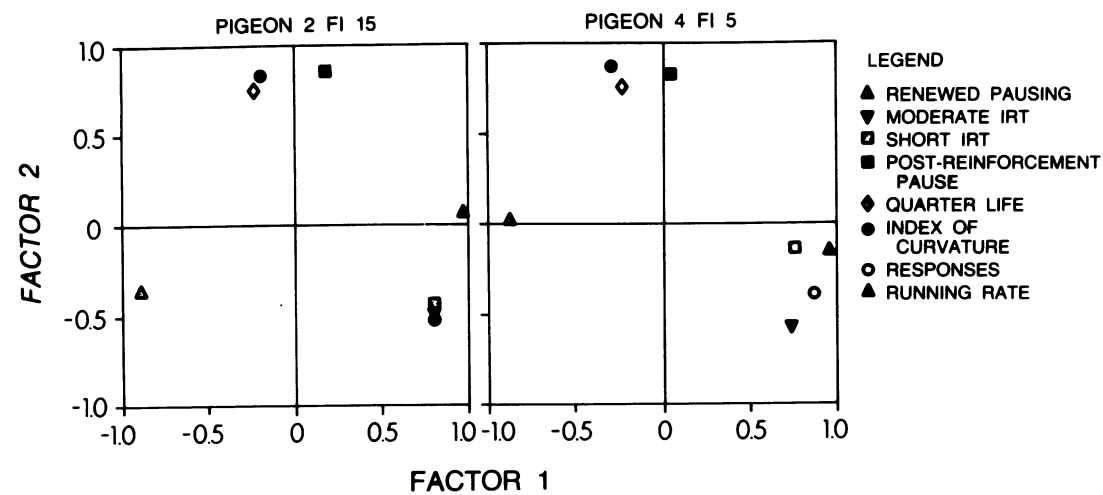
Fig. 11. Results of factor analysis of FI responding. These panels show the loadings of time spent in renewed pausing, moderate IRTs, short IRTs, postreinforcement pauses, quarter life, index of curvature, responses, and running rate. These results are from a varimax rotation of a principal-components analysis of the intercorrelation matrices shown in Table 2.

relationship to be positive or negative can therefore be assessed by how many were positive or negative. Specifically, with 21 sessions the probability of 5 (or fewer) positives or 15 (or more) positives is less than .03 if there is no correlation. The lag-1 correlations that exceeded these criteria are marked with an asterisk in Table 4. By applying such a test to these 50 correlations, it is expected that less than two would be significant by chance. Twenty-one correlations appeared to be consistent, far too many for a chance outcome. As pointed out by Gentry and Marr (1982), although these correlations are small, their consistency indicates that there is indeed a significant influence of one interval on the next. Furthermore, such dynamics are not restricted to responses and postreinforcement pauses.

GENERAL DISCUSSION

There has been no comprehensive account of the variables controlling FI responding (Zeiler, 1979), a shortcoming attributable to

Table 4

Lag-1 correlation matrix for measures of FI responding. These values are the means for 21 sessions. Those marked with (*) were consistently positive or negative (P < .03) across sessions.

| | | Interval N + 1 | | | | |
	P2 FI 15	A	B	C	D	E
	A. Response	−0.18*	0.10	0.08*	−0.16*	0.04
	B. Post-reinf. Pause	0.07*	−0.07	−0.07	0.03	0.05
Interval N	C. Index of Curvature	0.18*	−0.07	−0.14*	0.16*	−0.05
	D. Running Rate	−0.11	0.06	0.02	−0.11	0.04
	E. Renewed Pausing	0.12	0.00	0.01	0.14*	−0.11

| | | Interval N + 1 | | | | |
	P4 FI 5	A	B	C	D	E
	A. Response	−0.11	0.30*	0.29*	−0.01	0.06
	B. Post-reinf. Pause	0.28*	−0.14*	−0.20*	0.23*	−0.16*
Interval N	C. Index of Curvature	0.25*	−0.16	−0.22	0.21*	−0.15
	D. Running Rate	−0.05	0.29*	0.27*	0.04	0.03
	E. Renewed Pausing	0.09	−0.23*	−0.21*	0.04	−0.03

inadequate analyses of the data. Fixed-interval schedules engender distinctive cumulative-record patterns that have been described as either accelerating in rate or marked by break-and-run. Different theoretical accounts have been advanced to explain each. All explanations seem to agree that the initial pause results primarily from the fact that responding is never reinforced immediately after the preceding reinforcer; i.e., the subjects discriminate a period of extinction. Why the first response occurs when it does and what controls the succeeding pattern of responding, have defied universally accepted explanations. Any explanation based upon smoothly accelerating response rates is bound to fail because, as we have shown, the observed increase in response rates is not well characterized as smooth acceleration. Any explanation based on a simple break-and-run pattern does not do justice to most of the existing FI data. The data from the present study suggest that there is no simple explanation of the pattern of responding. The behavior of a pigeon is under very complex control. Indeed, there is an elegant pattern in the responding, both within the interval and across intervals.

The present analyses direct us toward the following conclusions: (1) Very long IRTs account for the curvature in cumulative records. (2) Very short IRTs occur with a rather uniform frequency throughout all ordinal positions of responses. (3) Moderate IRTs become more frequent as responding proceeds. (4) There is a sequential dependency in pairs of IRTs. (5) Two factors, which might be called "output" and "FI pattern," account for most of the variance in responding. (6) There is a complex sequential dependency across intervals.

Based on these conclusions, and data from other experiments, the following account is offered. The initial pause in the interval results primarily from extensive experience in which reinforced responses never occur soon after a reinforced response or stimuli associated with it. The pause duration is also partly determined by the response pattern in the preceding interval; a longer pause tends to follow a high response output and shorter pause. The first responses in an interval are likely to be high-rate bursts separated by renewed pauses. These renewed pauses account for the poor correlation between the postreinforcement pause and total responses. Without the re-

newed pauses, responding would be more like break-and-run and the correlation would be higher. Pauses with high-rate bursts are descriptions often given for extinction (Morse, 1966). Thus, this early portion of responding conforms more to extinction than to reinforced responding (as in a delay-of-reinforcement gradient). There is little information from this study on what contributes to this renewed pausing, especially what determines the duration and temporal or ordinal location of these pauses. The main clue is that these renewed pauses tend to occur early in the interval. Terminal responding appears to be a mixture of moderate and short IRTs that tend to alternate. Since the moderate IRTs are reinforced more frequently and are likely to follow short IRTs, it may be that pairs of alternating IRTs are reinforced. Since the sequential dependencies in IRTs may be longer than pairs, extended patterns of responding may actually be reinforced (cf. Weiss & Gott, 1972).

In summary, three distinct segments of FI responding may be identified. First, there is a pause associated with reinforcement; second, there is a period of alternating pausing and high-rate bursting; finally, the terminal pattern of responding predominates. The second phase accounts for the difference in previous explanations based upon accelerating rates versus break-and-run. This three-phase description is also in accord with data on interim behavior. Previous studies have shown that interim types of behavior are infrequent initially, increase as time into the interval proceeds, and then fade as terminal responding develops (Killeen, 1975; Roper, 1978, 1980). The exact relationship between our data and published models of interim types of behavior is not clear because these models are based on average time spent in these activities and, also, provide more information about the topography of these interim (or transition) activities. The appropriate data would show how interim behavior relates to responding with individual intervals. Clearly, the caveats on averaging performance across intervals should also apply to behavior other than key pecks. That is, average interim behavior may no more reflect what occurs within an interval than an average scallop reflects any single interval performance. The interim behavior may (scalloped records) or may not (break-and-run) include key-peck responses. When key pecks do

occur during the second phase, the pattern is unlike that found during the third phase.

Zeiler (1979) stated that the appropriate level of analysis depends upon the ultimate ability of the derived laws to "further the understanding of both larger and smaller portions of behaviour" (p. 79). Accounts based on performance averaged across intervals have failed to further our understanding of individual intervals. Within-interval analyses based on averaging across bins do not reflect results based on individual IRTs. So, by Zeiler's criterion, we must look to the individual IRTs and their sequential properties for an appropriate level of analysis. Whether or not this molecular level will prove adequate for explaining the larger structure in responding has yet to be determined.

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